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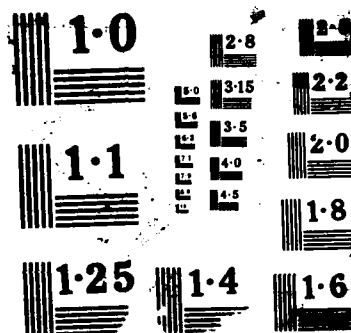
PHENOMENA AT A FOCUS IN A LASER SYSTEM

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A high-powered, continuous beam laser system is examined in terms of the physical conditions which exist if the laser beam is brought to a diffraction-limited, real focus in a moderate vacuum environment. Ionization of the gas at the focus by multiphoton processes is extensive, but it is shown that neither reflection of the beam by the plasma at the focus nor absorption by ionization is sufficient to disrupt propagation of the beam through the focus.

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FOREWORD

A high-powered, continuous beam laser system is examined in terms of the physical conditions which exist if the laser beam is brought to a diffraction-limited, real focus in a moderate vacuum environment. Ionization of the gas at the focus by multiphoton processes is extensive, but it is shown that neither reflection of the beam by the plasma at the focus nor absorption by ionization is sufficient to disrupt propagation of the beam through the focus.

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CHAPTER 1

INTRODUCTION

An investigation is made of the consequences of having a real focus in a single-pass, high-power, continuous-wave laser system. Specifically, the possibility is examined that gas molecules in the laser focus, upon ionization, can either reflect or absorb unacceptable fractions of the laser power.

PREVIOUS WORK

The same basic concerns treated here are the subject of an investigation by G. Gallatin[1] of the Perkin-Elmer Corporation. He starts with a general discussion of avalanche ionization, although he does not apply this work to the problem at hand. He then raises the subject of direct multiphoton ionization (for which he assumes a perturbation type of theoretical transition rate) and concludes that ionization at the focus will be total. He speculates that this will be of little consequence for propagation of the laser beam.

PLAN OF THIS PAPER

An assumed set of laser parameters is combined with a very high assumption for the density of gas molecules in the laser focus. The object is to hypothesize a set of conditions which is pessimistic for evaluation of the prospects for disruption of the propagation of the laser beam. If the conclusion is that the beam is free of significant disturbances at the focus, that conclusion can be accepted as reliable. If, on the other hand, it is found that disruption will occur, then the hypotheses must be examined more closely.

It is shown that the physical environment at the laser focus is well beyond the scope of perturbation theory. This justifies treatment of the photo-ionization of the gas molecules within the laser focus by a high-order, high-intensity, asymptotic result equivalent to tunneling through a potential barrier. Numerical results from an explicit calculation of the transition rate yield the conclusion that ionization at the focus will be total. It is then necessary to consider the consequences of this for continued propagation of the laser beam through the focus.

Excessive scattering of the beam out of the focal region is discounted by showing that the characteristic plasma frequency at the focus is below the laser frequency. The rate at which energy is absorbed from the beam by the photo-ionization process is evaluated under the very pessimistic assumption that ionized molecules will migrate away from the focus at a rate equal to that

at which new plasma can be generated by the laser. It is concluded that a sufficiently small fraction of the laser energy is absorbed by this mechanism that the beam will not be substantially depleted.

CHAPTER 2

CONDITIONS AT THE FOCUS

The laser under consideration produces continuously 10^8W of 3 µm radiation. The smallest focus that can reasonably be presumed has a diameter of about 10 µm. Furthermore, the focal region will be taken to be spherical rather than the elongated volume normally encountered. The resultant energy flux at the focus with these assumptions is 1.3×10^{14} W/cm^2.

The significance of this figure is to be evaluated in terms of the two relevant intensity parameters associated with multiphoton ionization.[2] The fundamental intensity parameter z is

$$z = \frac{e^2 E^2}{4m\hbar\omega^3} \tag{1}$$

in either cgs or mks units, where E is the amplitude of the laser's electric field, ω is its angular frequency, and e and m are the charge and mass of the electron. With fundamental physical constants substituted in Equation (1), z can be re-expressed as

$$z = 0.0753 \, \lambda^3 P, \tag{2}$$

with λ the field wavelength in cm and P the laser energy flux in W/cm^2. This gives the value z = 260 for the assumed conditions at the laser focus. A value of unity for z identifies a true intense field regime, and many of the recent multiphoton ionization experiments have been carried out at intensities corresponding to z values of 1 to 3.[3-7] Thus, z≈260 represents an extremely intense field environment, well into the asymptotic domain. In particular, it is so intense as to preclude any applicability of perturbation theory.

It remains to be ascertained whether this intensity implies that the mechanism for ionization can be regarded as a tunneling process. That is assessed in terms of the second intensity parameter, z_1, defined by

$$z_1 = 2z / (E_B/\hbar\omega), \tag{3}$$

where E_B is the initial binding energy of the detached electron.[2] Typical values for E_B for simple gas molecules like N_2, O_2, CO_2, or H_2O are of the order of a Rydberg, or about 13.6 eV. To be conservative, a figure of 10 eV will be used, and $\hbar\omega$ for 3 µm radiation is approximately 0.41 eV, so z_1 is about 20. This places the laser focus environment clearly in the

tunneling regime, since $z >> 1$, $z_1 >> 1$ are the necessary conditions for such a conclusion.[2] Among laboratory experiments, only the recent CO_2 laser results of the Université Laval group[8] fall unambiguously in this category.

CHAPTER 3

IONIZATION TRANSITION RATE

To calculate specific transition rates for multiphoton ionization, it is necessary to assume a specific initial state wave function. However, it is known that the outcome of the calculation depends primarily on the field conditions, and that it is relatively insensitive to the choice of initial bound state wave function.[9] A hydrogenic ground state wave function is chosen as a simple generic model for this purpose.

The necessary transition rate can be found most directly from the tunneling calculation presented by Keldysh.[10] When expressed in terms of the dimensionless parameters z and z_1 of Equations (1) and (3), the Keldysh result for the single electron ionization transition probability per unit time is

$$W = (2^{1/2} 3\pi)^{1/2} \; \omega \frac{z^{3/2}}{z_1^{5/4}} \; \frac{1}{(1+z_1)^{1/2}} \exp \left[-\beta \left(1 - \frac{1}{10z_1} \right) \right] , \tag{4}$$

in which the Coulomb correction factor

$$C = 2z/z_1 (1 + z_1)^{1/2} \tag{5}$$

has been incorporated, and where

$$\beta = 8z/3z_1^{3/2} . \tag{6}$$

With $z = 260$ and $z_1 = 20$, the outcome of Equation (4) is $W = 2 \times 10^{13} \; s^{-1}$.

No specification has yet been made for the density of gas molecules in the focal region. Two quite high numbers will be considered here. One, equivalent to one-tenth of an atmosphere at standard temperature and pressure, would amount to a density of 2.5×10^{18} molecules/cm^3. The other, corresponding to one Torr of pressure, yields 3.3×10^{16} molecules/cm^3. For the assumed size of the focal region, these figures lead to 1×10^9 and 2×10^7 molecules in the focus. When confronted with the ionization transition rate of $2 \times 10^{13} \; s^{-1}$, these numbers lead to the conclusion that ionization in the focal region is nearly total. A full treatment of the problem would require solution of rate equations for ionization as balanced against spontaneous and stimulated recombination, including direct processes as well as pathways involving excited bound states and autoionizing states of the molecules. Furthermore, transport of ionized and excited molecules out of the focus and diffusion of cold gas into the focal region are also important aspects of the problem. Detailed treatment along these lines is inappropriate here, and inconsistent with the broadly approximate

nature of the hypothesized physical conditions. An assumption of total
ionization is consistent with selection of simple but pessimistic hypotheses.

CHAPTER 4

SCATTERING FROM THE FOCUS

With the gas in the focus largely or completely ionized, the environment in this region is that of a plasma. The plasma frequency ω_0 depends entirely on the density, since

$$\omega_0 = (4\pi\rho e^2/m)^{1/2} , \tag{7}$$

where ρ is the density of charged particles. On the assumption of complete ionization, with a single electron detached from each molecule, the two hypothesized densities of 0.1 atmospheres and 1 Torr yield results in Equation (7) of 9×10^{13} and 1×10^{13} rad/s, respectively. The laser angular frequency corresponding to 3 μm wavelength is $\omega_L = 6.3 \times 10^{14}$ rad/s. In both cases, the laser frequency is above the plasma frequency, and so the laser beam is not denied access to the focal region. Had the reverse conclusion been obtained, the laser would be unable to penetrate the plasma at the focus, and beam propagation would be disrupted until the plasma density subsided to the point where the plasma frequency was below the laser frequency. A plasma frequency equal to the laser frequency is the critical value, and this corresponds to 10^{20} charged particles/cm^3 - a very large density.

CHAPTER 5

ABSORPTION IN THE FOCUS

Energy loss from the laser beam in the focus is evaluated on the basis that recombination in the focus and diffusion of ionized particles out of the focal region occur at the rate at which ionization by the laser beam is possible. With the rate at which energy in the focus is lost denoted by U, then

$$U = WV\rho E_B , \qquad (8)$$

where W is the ionization transition rate, V is the focal volume occupied by gas molecules with a density ρ, whose ionization energy is E_B. The hypothesized values of ρ of 1/10 atmospheric density and 1 Torr yield results of 4×10^4 watts and 5×10^2 watts from Equation (8). Since 10^8 W of laser power pass through the focus, these results correspond to 0.04 percent and 0.0005 percent power loss, based on our pessimistic assumptions.

Two supplementary remarks about Equation (8) must be made. One is that the ionization energy employed in Equation (8) is really not simply the no-field binding energy of the electron, since it is known that intense field photo-ionization has an energy threshold that increases with intensity.[2,11] That additional energy must be supplied by the laser as well as the basic ionization energy. The extra energy per ionization event is given directly by $z\hbar\omega_l$, with z as given in Equation (1). Since $\hbar\omega_l$ is 0.41 eV and z is 260, the increment is about 100 eV, which is far higher than any realistic no-field molecular ionization energy. Since 10 eV per ionization event was previously employed in Equation (8), those numbers would be increased by an order of magnitude to yield results of 0.4 percent and 0.005 percent loss of laser power in the focus. The physical basis for the intense field increment in ionization threshold is that in order for an electron to be promoted from a bound state to a detached state in the presence of the field, it must be supplied both with the binding energy and with the interaction energy of a free electron with the field. It is this last quantity which has the magnitude $z\hbar\omega_l$. However, upon departure of the detached electron from the laser focus, that extra energy is returned coherently to the laser field. This statement is based upon theory, since no experimental verification of this matter has yet been assayed. In summary, the true result for energy loss is then somewhere between the two sets of numbers quoted above.

The other remark that must be made is that no account has been taken of multiple ionization which will occur in intense fields. The multiple ionization which has been observed appears to occur in stepwise fashion, with second ionization occurring only in singly ionized atoms, and third ionization occurring only in doubly ionized atoms.[8] Since second and third ionization

energy thresholds are generally well above those for first ionization, the required multiphoton order becomes very large, with a corresponding increase in the necessary intensity at which ionization will occur. The z values required in Reference 8 for the observation of higher states of ionization were in the neighborhood of 10^3 to 10^4, at least an order of magnitude higher than the values present in the laser environment being explored here. This effect can be neglected.

CHAPTER 6

CONCLUSIONS

Under a set of pessimistic assumptions about ambient gas density, it has been shown that a continuous wave laser of 3 μm wavelength and 10^8 W power will successfully propagate through a diffraction limited focus. The criteria examined center on absorption of the beam in the focus and scattering of the beam out of the focal region. Not considered are ancillary effects on other parts of the system. Specifically, under the assumption of gas density at the focus corresponding to 10 percent of a standard atmosphere, it is estimated that as much as 0.4 percent of the laser energy could be absorbed in ionization events. This represents 4×10^5 W of power, much of it in the form of fairly energetic electrons. Secondary effects outside the focus stemming from this considerable power loss have not been examined.

REFERENCES

1. Gallatin, G., Subj: Laser-Induced Breakdown, internal Perkin-Elmer Corporation memo addressed to C. Roychoudhuri, 17 Jun 1986.

2. Reiss, H. P., Phys. Rev A, Vol. 22, 1980, p. 1786.

3. Lompre ., L. A., L'Huiller, A., Mainfray, G., and Manus, C., J. Opt. Soc. Am. B, Vol. 2, 1985, p. 1906.

4. Johann, U., Luk, T. S., Egger, H. and Rhodes C. K., Phys. Rev. A, Vol. 34, 1986, p. 1084.

5. Bucksbaum, P. H., Bashkansky, M., Freeman, R. R., McIlrath,T. J., and DiMauro, L. F., Phys. Rev. Lett., Vol. 56, 1986, p. 2590.

6. Hippler, H., Schwier, H., Humpert, H. J., and Lutz, H. O., Zeitschrift fur Physik D, Vol. 5, 1987, p. 21.

7. Reiss, H. R., J. Phys. B, Vol. 20, 1987, p. 179.

8. Yergeau, F., Chin, S. L., and P. Lavigne, J. Phys. B, Vol. 20, 1987, p. 723.

9. Reiss, H. R., J. Opt. Soc. Am. B, Vol. 4, 1987, p. 726.

10. Keldysh, L. V., Sov. Phys. JETP, Vol. 20, 1965, p. 1307.

11. Kruit, P., Kimman, J., Muller, H. G., and van der Wiel, M. J., Phys. Rev. A, Vol. 28, 1983, p. 248.

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